

DIFFICULTIES OF PRESERVING THE LEAP SECOND

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SUMMARY: In this article we examine the possibility to extend leap second extrapolation for a near future based on some periodic terms in the Earth's rotation changes. The IERS data, covering the interval from 1962.15 to 2006.95, are analyzed. The difference ΔT is extrapolated till to 2035 and compared with the IERS extrapolated values to the 2012. It can be seen that for the interval from 2006 to 2024 only 1 leap seconds (negative) will be operated.

Key words. Earth, Time

1. The leap second

The recommendations of the IAU (International Astronomical Union) were formalized by resolutions of their Commissions that the name *UTC* (abbreviation is compromise between English Coordinated Universal Time and French Temps Universel Coordonné) was retained. *UTC* was recommended as the basis of standard time in all countries, the time in common (civil) use. The limit of $[UT1 - UTC]$ (*UT1*, Universal time) was set at +0.950s, as this is the maximum difference that can be accommodated by the code format. The maximum deviation of *UT1* from $[UTC + DUT1]$ (time correction $DUT1 = UT1 - UTC$) was set at +0.100s. In 1974, the CCIR (Consultative Committee on International Radio, En. or Comité consultatif international pour la radio, Fr.), increased the tolerance for $[UT1 - UTC]$ from 0.7s to 0.9s. The present *UTC* system is defined by ITU-R (International Telecommunication Union – Radio) (formerly CCIR) Recommendation ITU-R TF.460-5:

"*UTC* is the time scale maintained by the

BIPM (Bureau International des Poids et Mesures, Fr. or International Bureau of Weights and Measures, En.), with assistance from the IERS (International Earth Rotation and Reference Systems Service), which forms the basis of a coordinated dissemination of standard frequencies and time signals. It corresponds exactly in rate with *TAI* (International Atomic Time, En., Temps Atomique International, Fr.) but differs from it by an integral number of seconds. The *UTC* scale is adjusted by the insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with *UT1*."

Because the Earth's rotation is gradually slowing down, and in addition it has both random and periodic fluctuations, it is not a uniform measure of time. The time difference $\Delta T = [ET - UT1] = [TT - UT1]$ represents the difference between the uniform scale of Ephemeris Time (*ET*) or Terrestrial Time (*TT*) and the variable scale of Universal Time (*UT1*). Before 1955, the values are given by $\Delta T = [ET - UT1]$ based on observations of the Moon. After 1955, values are given by $\Delta T = [TT - UT1] = [TAI + 32^s.184 - UT1]$ from measurements by atomic clocks as published by the BIH (Bu-

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reau International de l'Heure, Fr. or International Time Bureau, En.) and the BIPM.

According to Stephenson and Morrison (1995), over the past 2700 years ΔT can be represented by a parabola of approximately the form

$$\Delta T = (31^s/\text{cy}^2)(T - 1820)^2/(100)^2 - 20^s.$$

where ΔT is expressed in seconds and T is the year. The minimum is at the year 1820 and passes through 0 at the year 1900. Actual values of ΔT based on astronomical data may differ somewhat from this smoothed fit. For example, the value of ΔT is $32^s.184$ at 1958.0, the origin of TAI . However, no single parabola can **satisfactorily represent** all the observational data.

The derivative of ΔT is

$$\Delta LOD = (0.0017 \text{ s d}^{-1} \text{ cy}^{-1}) \frac{(T - 1820)}{100}.$$

which represent the change of the length of day (LOD) in SI seconds. Different studies implies different values. The actual value of the LOD will depart from some long-term trend with short-term fluctuations (periodicity) between ± 3 ms on time scale of decades.

Similarly, the insertion of leap seconds is due to the fact that the present length of the mean solar day is about 2.5 ms longer than a day of precisely 86400 SI seconds, as a consequence of the long-term trend, so that the Earth's rotation runs slow with respect to atomic time.

2. The data and model

UTC is kept within 0.9 s of $UT1$ by the occasional insertion of a leap second adjustment. When the present UTC system was established in 1972, the time difference $\Delta T = [TT - UT1] = [TAI + 32^s.184 - UT1]$ was equal to 42.23 s. Thus the difference between TAI and $UT1$ in 1972 was approximately 10 s. To maintain continuity with $UT1$, UTC was initially set behind TAI by this amount. As of January 1st, 2006 the 23 positive leap seconds have been added. Thus UTC is presently behind TAI by 33 s. Figure 1 illustrates the relationships between TAI , UTC and $UT1$ (IERS data).

A least-squares fit of the difference [$UTC - TAI$] since 1972, shown in Figure 1, implies a nearly linear increase with a slope of (2.10 ± 0.05) ms per day. This value represents the average excess in the length of day during the past three decades and is in approximate agreement with the value computed on the basis of the long-term trend.

Recent global weather conditions have contributed to a short-term change in the length of day. Decade fluctuations due to the interaction between

the Earth's core and mantle and global ocean circulation may also contribute. The model characterized by triaxial Earth's structure, its fluid core, viscoelastic mantle and equilibrium ocean was proposed by the Vondrák (1987).

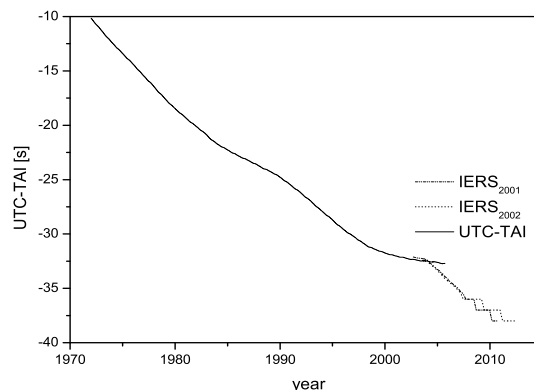


Figure 1. $UTC - TAI$ as extrapolated by IERS at 2001 and 2002 compared with observed values of $UTC - TAI$ till 2006.

As a contrary Yoshido and Hamano (1993) have proposed that one of the main causes of the secular variation of the geomagnetic field is length-of-day (LOD) variation, namely, the variation of the rotation velocity of the mantle. They developed an analytical model, in which fluctuations of the rotation velocity of the mantle induce flow in the outer core through topographic coupling at the core-mantle boundary (CMB). The flow in turn bends the toroidal field to produce a poloidal field.

At periods longer than few years, extending to many tens of years, the so-called *decadal variations*, the sources of excitation for both LOD and PM are more enigmatic. The difficulty is that at these periods other effects may be important, including viscoelastic behavior such as post-glacial rebound, and exchange of angular momentum with the fluid core. In particular, it has become common to invoke the core as the major cause of decadal LOD changes. Although some climatic forcing of long period LOD has been recognized (Salstein and Rosen, 1986; Eubanks, 1993), it is uncertain at what time scale air and water become less important than the core. Unfortunately, the role of the core remains largely unquantified because it is too remote to be easily observed. A further difficulty in assessing the air/water role at long periods is that the torques required to cause decadal LOD variations are utterly insignificant when compared with those applied by the atmosphere at shorter time scales (Hide and Dickey, 1991). This means that atmospheric/oceanic torques of geodetic significance are of second-order importance in general circulation studies. Quantification of momentum budgets among Earth, air, and water reservoirs is thus lacking at long periods. The requirements for progress in this field coincide com-

pletely with the central problems of global climate change.

The five Earth Orientation Parameters (EOP) - two components of polar motion x, y , two components of celestial pole offsets $\Delta\psi, \Delta\epsilon$, and universal time $UT1$ (that is nothing else but the angle of Earth's rotation around its spin axis) - are now analyzed and routinely derived from the observations at several world's centers, combined and regularly published in IERS bulletins. The most recent system of constants and algorithms (McCarthy, 1996, Vondrák, 1998) are used. The past solutions based on optical astrometry were merged with the combined solutions from the modern techniques (Vondrák, 2001).

The existing ERP (Earth Orientation Parameters) series have been analyzed by many scientists. The most extensive reviews, with historical meaning, were given in well-known monographs by Munk & MacDonald (1960) and Lambeck (1980). Most recent of these analyses is that by Zharkov et al. (1996). A very detailed review, mostly concentrated on modern space techniques and discussion of short-periodic effects, was published by Eubanks (1993). Moreover, in our previous paper (Šegan et al., 2003) we have introduced the relax period as good explanation of the residuals in the $(UT1 - UTC)_{BLI}$ data.

The motivation for the leap second, therefore, is due to the fact that the second as presently defined is "too short" to keep in step with the Earth. However, had the second been defined **to be exactly equal** to a mean solar second at the origin of TAI in 1958, the discrepancy **would not have been removed; the agreement** between the SI second and the mean solar second would have only been **temporary** and their difference would simply have become gradually more apparent over this century.

Continuing use of a non-uniform time scale including leap seconds in the face of these considerations could lead to the necessity to proliferate an effective method for extrapolation of the future values of ΔT .

To try that, according to our analysis of the IERS ΔT data from 1962.15 to 2006.95, existence of some periodic terms is discovered. By using the harmonic analysis 17 components plus a linear term of equation (1) are determined.

$$M\Delta T_i = C_1 + C_2 \times t_i + \sum_{j=1}^{17} A_j^c \cos\left(\frac{2\pi}{P_j} \cdot t_i\right) + A_j^s \sin\left(\frac{2\pi}{P_j} \cdot t_i\right). \quad (1)$$

In equation (1) $M\Delta T_i$ is a modified ΔT_i . In order to obtain the ΔT_i values one needs to perform a translation by a constant value of $32.184 + 10$ seconds:

$$\Delta T_i = 32.184 + 10 - M\Delta T_i.$$

Table 1. The coefficients for 17 components obtained from the harmonic analysis.

j	A_j^c	A_j^s	σ_j^2	P_j
1	5.634826	-46.439608	.20	222.28
2	-.531603	.283347	.027	19.54
3	-.051990	.172145	.011	12.54
4	-.001363	-.117686	.0039	46.04
5	-.037362	.009689	.0021	22.22
6	-.029915	.004394	.0016	5.84
7	-.017975	.018877	.0013	7.90
8	-.002987	-.020452	.0011	1.00
9	-.007429	.017729	.00090	6.50
10	-.004306	.016504	.00076	4.63
11	-.000759	.016891	.00062	9.26
12	.002933	-.013173	.00052	3.57
13	-.010059	-.006987	.00045	5.28
14	-.001567	-.010152	.00040	4.08
15	.006573	.007869	.00034	.50
16	-.002887	.004019	.00033	1.09
17	.000452	-.000316	.00033	.17

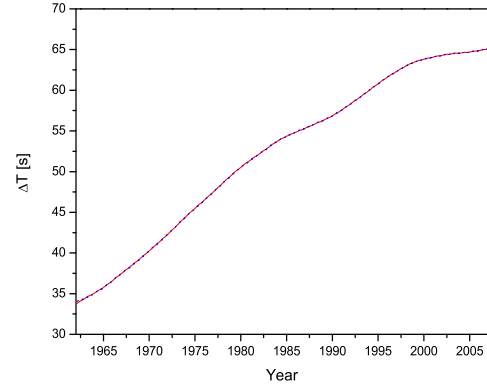


Figure 2. The dashed line (blue) represents IERS data and the solid one (red) represents our approximation (prediction) between 1962.15 and 2006.95.

The coefficients of the linear function (in equation (1)) are: free term $C_1 = 3.408457$ and slope coefficient $C_2 = 0.357042$. The coefficients of the harmonic components are given in Table 1. σ_j^2 is the upper limit for the coefficients of the harmonic components (it is the same for both coefficients, A_j^c and A_j^s) and it is given with two significant digits. The

periods P_j are given in years. Because of the secular and decade variations all terms corresponding to insignificant periods and amplitudes (smaller than few milliseconds) are on the noise level so that they are not determined.

In Fig. 2 the dashed line (blue) represents the IERS data from 1962.15 to 2006.95, whereas the solid one (red) represents our approximation for the period between 1962.0 and 2007.0. One can notice an excellent agreement.

According to our approximation till 2024 there is practically no need to introduce leap seconds because an accumulation of 0.9 seconds is reached as late as at 2014.0, i. e. an accumulation of one second in 2015. The local maximum in our approximation occurs at 2016.4 and its value is 65.944 which exceeds the difference of one second by 0.1 seconds only (Fig. 3). In view of the further negative trend of our approximation the next leap second (negative) should be introduced in 2024 if the difference of 0.1 seconds at the moment of approximation maximum were neglected.

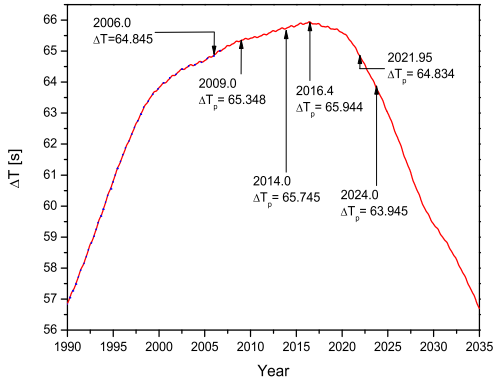


Figure 3. The approximation from 1990 to 2035 and IERS data till 2006.95. The indicated points are: the moment when the leap second was introduced for the last time (2006), the next introducing (2009), the point at which according to our approximation the difference of 0.9 seconds between UT1 and UTC is reached (2014.0), the local maximum of our approximation (2016.4), the point for which ΔT is approximately the same as in 2006 when the leap second was introduced for the last time (2021.95) and the point when, according to our approximation, the next leap second (negative) should be introduced (2024.0). Note that this means to introduce only one negative leap second within 18 years (2006–2024).

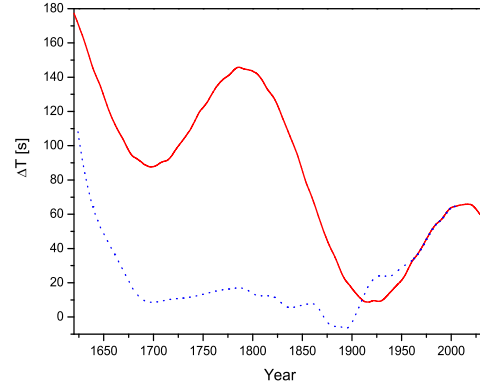


Figure 4. The historical observations covering the period 1620–2006.95 are represented by the dashed line (blue) and our approximation concerning the interval 1620–2035 by the solid line (red).

4. CONCLUSIONS

As the day at present is actually closer to 86400 SI seconds the leap seconds have not been required regularly. However, this condition cannot persist and the long or mid-term trend will be eventually restored. The asymptotic behaviour of the ΔT in the Stephenson–Morrison approximation (1995) is not natural.

As can be seen from the analysis (Fig. 4) applied within a relatively short time interval, 1962.15–2006.95, the extrapolation of the ΔT value agrees well with both the historical values (1620–1962) and the real measurements from 1962.15 to 2006.95. The discrepancy in the amplitude is higher for the former period, but the agreement for the phase is very good which indicates that the approximation could be improved if a bigger set of measurements were available.

Our conclusion, that the first (additional) leap second should be introduced in 2014 only, opposes to all the extrapolations proposed till nowadays by both international institutions and individual experts. The majority of them predicts 2008 as the year when the additional correction should be introduced.

The values attained by ΔT are of such order that all the physical factors unambiguously recognized till nowadays cannot cause such a phenomenon and in this sense the present analysis means a strictly mathematical approximation only. We believe that the years to come will show the correctness of the obtained results.

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ТЕШКОЋЕ У ОЧУВАЊУ ПРЕСТУПНЕ СЕКУНДЕ

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Испитана је могућност да се прогнозира број преступних секунди у блиској будућности на основи познавања неколико хармонијских компоненти у Земљиној ротацији. Анализирани су подаци IERS-а који обухватају интервал од 1962,15 до 2006,95. Разлика ΔT је ек-

страполирана до 2035. године и упоређена са предвиђањима IERS-а до 2012. године. Може се видети да је у интервалу од 2006. до 2024. године потребно увести само једну (негативну) преступну секунду.